# 2 Surficial Erosion and Mass Movement

## 2.0 INTRODUCTION

Hills and uplands form as the result of tectonic forces that warp the earth's crust. Plutonic rock masses can also push up through the crust, forming mountain ranges such as the Sierra Nevada. Volcanic activity may bring up molten rock from the earth's interior and deposit it on the surface to create mountains and volcanoes as well. These mountainous areas and uplands in turn are subject to degradation and wear by the twin processes of surficial erosion and mass movement. Man-made slopes, for example, cuts and embankment slopes, are subject to the same degradation processes.

In order to control or prevent this wearing or wasting away of the earth's surface, it is first necessary to understand these two processes of degradation and the factors that control them. While the two processes share many similarities, they also differ in important respects. Surficial erosion entails the detachment and transport of individual particles whereas mass movement entails the movement of relatively large, initially intact masses of soil and/or rock along critical failure surfaces. Gravity is the main driving force behind mass wasting; wind and running water are the principal agents of erosion. The role and function of vegetation also differ substantially between these two processes.

## 2.1 DEFINITIONS

### 2.1.1 Surficial Erosion

Surficial erosion or soil erosion is the removal of surface layers of soil by the agencies of wind, water, and ice. Soil erosion involves a process of both particle *detachment* and *transport* by these agencies. Erosion is initiated by drag, impact, or tractive forces acting on individual particles of soil at the surface. Weathering processes such as frost action and wet-dry cycling set the stage for erosion by breaking up rock into smaller particles and weakening bonds between particles.

The two most common types of erosion are rainfall and wind erosion. Rainfall erosion starts with falling raindrops themselves. When these drops impact on bare or fallow ground, they can dislodge and move soil particles a surprising

distance. At the onset of runoff, water collects into small rivulets, which may erode very small channels called rills. These rills may eventually coalesce into larger and deeper channels called gullies. Gullying is a complex and destructive process; once started, gullies are difficult to stop. Bare or unprotected earth surfaces are the most vulnerable to all forms of surficial erosion.

Erosion may also occur along streambanks where the velocity of the flowing water is high and the resistance of the bank material often low. Continuous or prolonged periods of inundation coupled with a variety of other degradation processes, also make streambank protection a formidable task. Piping or spring sapping is yet another type of erosion, in this case caused by seepage and emergence of water from the face of an unprotected slope.

### 2.1.2 Mass Movement

Mass movement is a descriptive name for the downward and outward movement of slope-forming materials—natural rock, soils, artificial fills , or combinations of these materials. The terms "mass erosion" or "mass wasting" are sometimes used. Mass movements are popularly known as landslides. Strictly speaking, however, landslides or slides refer to a particular type of mass movement.

Unlike soil erosion, mass movement involves the sliding, toppling, falling, or spreading of fairly large and sometimes relatively intact masses. Mass movements have been classified into categories based largely on the type of movement and material involved (Varnes, 1978). A slide is a relatively slow slope movement in which a shear failure occurs along a specific surface or combination of surfaces in the failure mass. Slides are amenable to quantitative stability analysis by techniques of limiting force equilibrium and limit analysis.

### 2.1.3 Salient Characteristics and Differences

Many of the same slope, soil, and hydrologic factors that control surficial erosion also control mass movement (e.g., steepness of slope and shear strength of soil). The two processes differ, however, in some important respects. The salient characteristics of surficial erosion on the one hand and mass movement on the other are contrasted in Figure 2-1. Precipitation, a key factor directly affecting rainfall erosion, only affects mass movement indirectly via its influence on the groundwater regime at a site. In contrast, geologic conditions such as orientation of joints and bedding planes in a slope, can have a profound influence on mass stability but not on surficial erosion. Vegetation has an important influence on both erosion and shallow mass movement.

Different predictive techniques or models have been developed to determine soil losses from surficial erosion or the likelihood of catastrophic slope failure in the case of mass movement. Rainfall and wind erosion, for example, are controlled by a number of soil, climatic, and topographic factors, including intensity and duration of precipitation, ground roughness, length and steepness of slope,

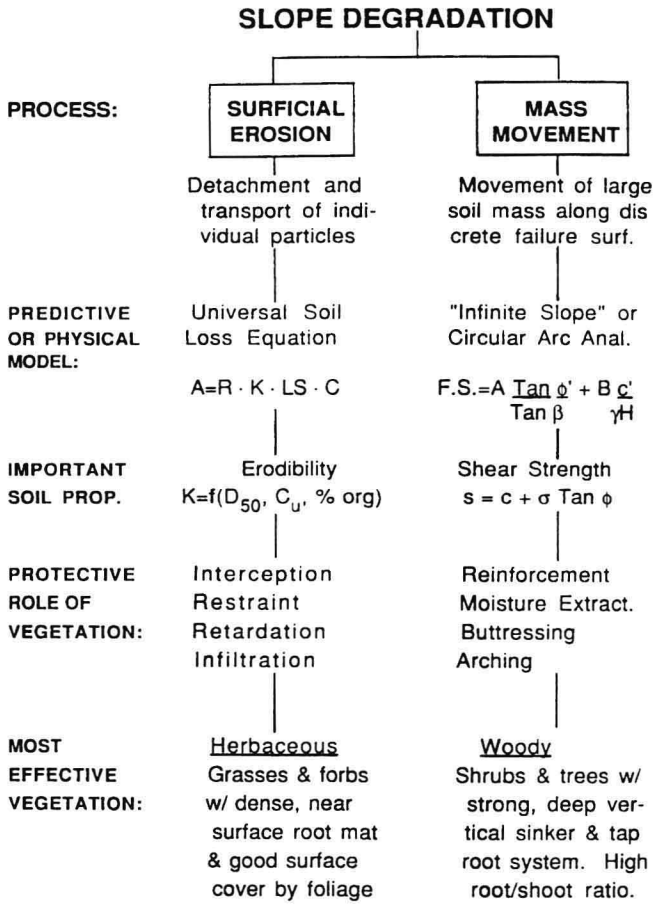


**Figure 2-1.** Salient characteristics of surficial erosion versus mass movement.

inherent soil erodibility, and type or extent of cover. All of these factors are taken into account explicitly in the universal soil loss equation (Wischmeier and Smith, 1978).

## 2.2 NATURE OF SURFICIAL EROSION

### 2.2.1 Agents and Types of Erosion

The primary agents of erosion include water, wind, and ice. These agents can scour and remove soil particles as a result of flowing past, impacting upon, or exiting from the surface of a soil. Each agent can also erode soil in quite different manners. Rainfall erosion, for example, can occur in the form of splash,

sheet, or rill erosion. The various agents and types of erosion are summarized in Table 2-1.

Degradation processes often act jointly or in combination with one another. Glaciated landscapes, for example, may be the product of glacio-fluvial processes. Ground disturbed by creep or solifluction is more vulnerable to rilling and gullying. Groundwater piping likewise can trigger or promote gullying.

### 2.2.2 Mechanics of Erosion

Prevention and control of erosion depends on understanding the mechanics of the erosion process. Erosion is basically a twofold process that involves:

1. Particle detachment
2. Particle transportation

The forces acting on particles near a fluid-bed boundary or interface are shown schematically in Figure 2-2. Drag or tractive forces exerted by the flowing fluid are resisted by inertial or cohesive forces between particles.

$$\text{Erosion is } \textit{caused} \text{ by: } \begin{matrix}\text{Drag or}\\ \text{tractive}\\ \text{forces}\end{matrix} \left(\begin{matrix}\text{Water,}\\ \text{wind,}\\ \text{ice}\end{matrix}\right) = f \left\{\begin{matrix}\bullet\ \text{Velocity}\\ \bullet\ \text{Discharge}\\ \bullet\ \text{Shape and roughness}\end{matrix}\right.$$

**TABLE 2-1. Agents and Types of Erosion**

| Agent | Type of Erosion or Degradation Process | |
|---|---|---|
| Water | 1. Raindrop splash | |
| | 2. Sheet erosion | |
| | 3. Rilling | |
| | 4. Gullying | |
| | 5. Stream channel erosion | |
| | 6. Wave action | |
| | 7. Piping and sapping | |
| Ice | 1. Solifluction | |
| | 2. Glacial scour | |
| | 3. Ice plucking | |
| Wind | Wind erosion cannot be subclassified into "types"; instead it varies mainly by "degree." | |
| Gravity | 1. Creep | These are usually classified under mass wast-ing, but they often act in conjunction with erosion |
| | 2. Earth flow | |
| | 3. Avalanche | |
| | 4. Debris slide | |

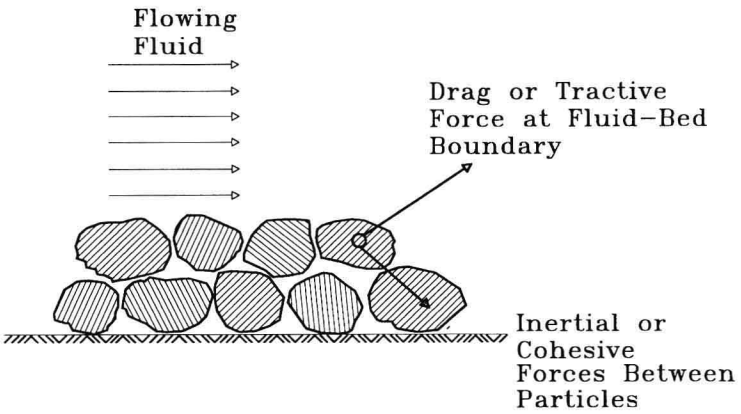


**Figure 2-2.** Schematic diagram of forces acting on particles at fluid-bed boundary.

Erosion is *resisted* by: Inertial, frictional, and cohesive forces $= f$ { • Basic soil properties • Soil structure • Physicochemical interactions

Erosion protection essentially consists of: (1) decreasing drag or tractive forces by decreasing the velocity of water flowing over the surface or by dissipating the energy of the water in a defended area, and (2) increasing resistance to erosion by protecting/reinforcing the surface with a suitable cover or by increasing interparticle bond strength.

## 2.3 PRINCIPAL DETERMINANTS OF EROSION

### 2.3.1 Rainfall Erosion

Rainfall erosion is controlled by four basic factors, namely, climate, soil type, topography, and vegetative cover. This relationship can be expressed schematically as follows:

$$\text{Rainfall erosion} = f \begin{cases} \text{Climate—storm intensity and duration} \\ \text{Soil—inherent erodibility} \\ \text{Topography—length and steepness of slope} \\ \text{Vegetation—type and extent of cover} \end{cases}$$

The most important climatic parameters controlling rainfall erosion are intensity and duration of precipitation. Wischmeier and Smith (1958) have shown that the most important "single" measure of the erosion-producing power of a

rainstorm is the product of rainfall energy times the maximum 30-minute rainfall intensity. Raindrops impacting on bare soil not only cause erosion; they also tend to compact the soil and decrease infiltration capacity.

The susceptibility of a soil to erosion is known as it "erodibility." Some soils (e.g., silts) are inherently more erodible than others (e.g., coarse, well-graded gravels). In general, increasing the organic content and clay size fraction of a soil decreases erodibility. Erodibility also depends upon such parameters as soil texture, antecedent moisture content, void ratio, exchange ions, pH, and composition or ionic strength of the eroding water. The dependence of soil erodibility on all these variables is summed up in Table 2-2.

There is no simple and universally accepted erodibility index for soils. Instead, various tests have been proposed for this purpose, including the SCS dispersion test (Volk, 1973), crumb test (Emerson, 1967), and pinhole test (Sherard et al., 1976). A suggested hierarchy of erodibility based on the Unified Soil classification system is:

$$\text{Most Erodible} \longrightarrow \text{Least Erodible}$$

$$\text{ML} > \text{SM} > \text{SC} > \text{MH} > \text{OL} \gg \text{CL} > \text{CH} > \text{GM} > \text{SW} > \text{GP} > \text{GW}$$

where:

GW = well graded gravel
GP = poorly graded gravel
GM = silty gravel
SW = well graded sand
SM = silty sand
SC = clayey sand
ML = low plasticity silt
MH = high plasticity silt
CL = low plasticity clay
CH = high plasticity clay
OL = low plasticity organic soil

This erodibility hierarchy is simple, but based on gradation and plasticity indices of remolded or disturbed soils. Accordingly, it fails to take into account effects of soil structure, void ratio, and antecedent moisture content. Wischmeir et al. (1971) published an erodibility nomograph for use with the universal soil loss equation (see Section 2.5) that is based on easily measured soil properties.

**TABLE 2-2. Soil Erodibility Trends**

- Is low in well-graded, coarse gravels
- Is high in uniform silts and fine sands
- Decreases with increasing clay and organic content
- Decreases with low void ratios and high antecedent moisture content
- Increases with increasing sodium adsorption ratio and decreasing ionic strength of water

Topographic variables influencing rainfall erosion are: (1) slope angle, (2) slope length, and (3) size and shape of watershed. The influence or importance of length tends to increase as slopes become steeper. For instance, a doubling of slope length from 100 to 200 feet will only increase soil losses by 29 percent on a 6-percent slope, whereas the same doubling of slope length in a 20-percent slope will result in a 49 percent increase in soil loss. This is one of the reasons for benching or terracing and contour wattling long, steep slopes.

Vegetation plays an extremely important role in controlling rainfall erosion. Removal or stripping of vegetation by either human or natural agencies (e.g., wildfires) often results in accelerated erosion. Conversely, any measure that either preserves or enhances vegetation establishment will significantly retard soil loss and minimize erosion. The protective mechanisms of vegetation in preventing both surficial erosion and shallow mass movement are discussed at length in Chapter 3.

### 2.3.2 Wind Erosion

Wind erosion is controlled by the same basic factors that control rainfall erosion. The dependence of wind erosion on these factors can be expressed schematically in a similar fashion as follows:

$$\text{Wind erosion} = f \begin{cases} \text{Climate—temperature, rainfall distribution} \\ \quad \text{wind velocity} \\ \text{Soil—texture, particle size, moisture content,} \\ \quad \text{surface roughness} \\ \text{Vegetation—type, height, and density of cover,} \\ \quad \text{seasonal distribution} \end{cases}$$

These factors again can be expressed in terms of identifiable and measurable parameters as noted above. Unlike rainfall erosion, topographic parameters such as length and steepness of slope are relatively unimportant in the case of wind erosion. On the other hand, surface roughness and the presence of low barriers that act as wind breaks and sediment traps can be important. The climatic factors that most affect soil moisture are amount and distribution of rainfall, temperature, and humidity. Only relatively dry soils are susceptible to wind erosion. The most important characteristics of the wind are its velocity, duration, direction, and degree of turbulence. Wind can only pick up and carry in suspension dry soils with particle sizes primarily less than 0.1 mm, that is fine silt size material.

Wind erosion consists of three distinct phases: initiation of movement (detachment), transportation, and deposition. Soil movement by wind is initiated as a result of turbulence and velocity. The velocity required to start movement increases as the weight of particles increases. For many soils, this velocity is about 13 mph at a height of 1 foot above the ground. The velocity required

**TABLE 2-3. Movement of Soil Particles by Wind**

| Mechanics of Movement | Size of Particles Moved (mm) | Percent of Soil Moved |
|---|---|---|
| Suspension | <0.1 | 3–38 |
| Saltation (skipping and bouncing) | 0.1–0.5 | 55–72 |
| Surface creep (rolling and sliding) | 0.5–1.0 | 7–25 |

*Source:* After Chepil (1945).

to sustain movement, once started, is less than that required to initiate movement. Similar relationships have been observed in the case of erosion by flowing water.

Laboratory studies by Chepil (1945) established that soil particles are transported by wind in the manner shown in Table 2-3. The major portion of soil particles transported by the wind occurs near the ground surface at heights under 3 feet (1 m). Approximately 62 to 97 percent of the total wind-eroded soil is transported in this zone near the surface, a fact that suggests the utility of installing relatively low barriers or windbreaks to filter and impede the movement of windborne soil. Vegetation readily serves this purpose in addition to its other control functions such as increasing surface roughness, slowing and deflecting the wind, and binding soil particles together. Because of these properties vegetation can be used very effectively in combination with fencing to trap drifting sand and build up dunes along beaches. Hardy, drought and salt tolerant plants, such as sea oats, beach grass, and bitter panicum, work well in this regard, as shown in Figure 2-3.

**Figure 2-3.** Dune vegetation helps to trap drifting sand and build foredunes shoreward of dry beach.

## 2.4 TYPES OF WATER EROSION

Water erosion manifests itself in many different ways. Rainfall erosion begins with raindrop splash and can progress ultimately to gullying and stream channel erosion. The salient characteristics of different types of water erosion are briefly reviewed next.

*Raindrop Splash:* Raindrop splash results from the impact of water drops falling directly on exposed soil particles or thin water surfaces covering the ground. Tremendous quantities of soil can be splashed into the air in this manner. On bare ground it has been estimated (Ellison, 1948) that as much as 100 tons/acre can be splashed into the air in a heavy storm. Splashed particles may move more than 2 feet vertically and 5 feet laterally on level ground. On steep slopes this splashing will cause a net downslope movement of soil.

*Sheet Erosion:* Sheet erosion is the removal of soil from sloping land in thin layers or sheets. From an energy standpoint raindrop erosion appears to be more important than sheet erosion because most raindrops have velocities of about 20 to 30 fps, whereas overland flow velocities are about 1 to 2 fps. Dry ravel and slope wash are forms of sheet erosion; the former occurs when surface layers of coarse-textured soil dry out and lose their apparent cohesion. The latter occurs when rainfall erodes without causing rilling or gullying. Sheetlike erosion is an important mechanism of slope retreat and source of sediment in cut slopes in granitic and andesite soils. Highway cuts in these soils often give the impression of being very stable (e.g., rills and gullies are absent) yet discharge tons of soil year after year into the roadside ditches (Howell et al., 1979).

*Rilling:* Rill erosion is the removal of soil by water from very small but well-defined, visible channels or streamlets where there is concentration of overland flow. An example of rill erosion at an urban construction site is shown in Figure 2-4. Rilling generally is more serious than sheet erosion because runoff velocities are higher in the rills or channels. Rilling is the form or erosion during which most rainfall erosion losses occur (Schwab et al., 1981). Rill erosion is most serious where intense storms occur in watersheds or sites with high runoff-producing characteristics and loose, shallow topsoil. Rills are sufficiently large and stable to be seen readily, but small enough to be removed easily by normal tillage and grading operations.

*Gullying:* Gullies are intermittent stream channels larger than rills. These channels carry water during and immediately after rains, and, unlike rills, gullies cannot be obliterated by normal tillage. Gullies tend to form where large volumes of runoff are concentrated and discharged onto steep slopes with erodible soils, e.g., undefended culvert outlets. Gullying is common in grasslands and is likely the principal form of erosion in steep, forested

**Figure 2-4.** Rill erosion at an urban construction site. Ann Arbor, Michigan.

watersheds. The dynamics of gully formation are complex and not completely understood. Various statistical models for predicting gully growth and development have been proposed (Beer and Johnson, 1963; Thompson, 1964). Gullies may not be as significant as rills in terms of total quantities of soil eroded, but they can be quite destructive in terms of damage to roadways, embankments, and watersheds as shown in Figure 2-5. They are also difficult to control and arrest. Effective gully control must stabilize both the channel bottom and headcuts. Continued downcutting of gully bottoms leads to deepening and widening, whereas headcutting extends the channel into ungullied headwater areas, and increases the stream net and its density by developing tributaries.

*Stream Channel Erosion:* Stream channel erosion consists of soil removal from stream banks and/or sediment scour along the channel bottom. Stream channel erosion should be considered separately from the rainfall-associated types of erosion discussed previously. A number of hydrologic/hydraulic and geomorphic variables govern the behavior of fluvial systems. These variables are in a dynamic equilibrium with one another. Investigators such as Leopold (1994), and Lane (1955) have determined several general relationships among these variables that are useful in analyzing stream activity. This balance or equilibrium will determine, for example, where material is likely to be eroded as opposed to deposited along a particular reach of stream.

Like gully erosion there are several processes acting along streams that

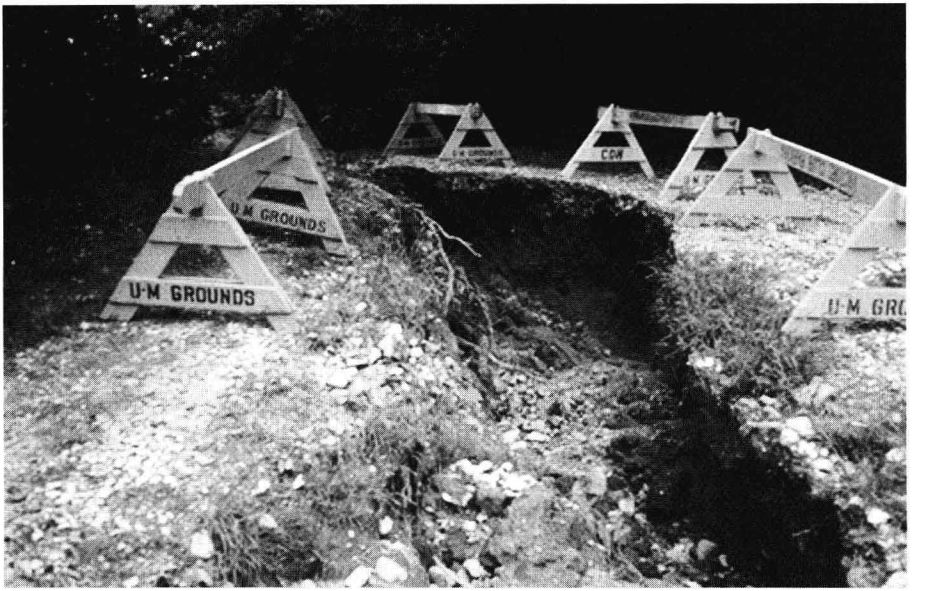


**Figure 2-5.** Hillside gully erosion caused by uncontrolled and concentrated discharge of runoff from parking lot.

are responsible for streambank and channel degradation (Keown et al., 1977). These include:

1. *Mass Wasting:* Slumping or sliding induced by undercutting, oversteepening, or impeded drainage during flood recession
2. *Flow Erosion:* Tractive stress imposed by flowing water
3. *Piping:* Seepage erosion as a result of bank drainage
4. *Wave Erosion:* Pumping action, pore pressure fluctuations, and wave run-up problems
5. *Freeze/Thaw Degradation:* Solifluction, volume instability, and impeded drainage

It is helpful to recognize and understand these processes when designing a prevention and control system. On the other hand, this classification of erosion processes is not particularly helpful in establishing the cause of stream channel and bank erosion. The cause must be linked to fluvial geomorphology and the play or relationship between hydraulic/hydrologic variables. From the stand-point of fluvial geomorphology, there appear to be three main actions or events (Keown et al., 1977; Leopold, 1994) that result in stream erosion:

1. *Widening:* Channel enlargement caused by increased streamflow and/or sediment discharges.

2. *Deepening:* Scouring of the channel bottom caused by increased flows and or changes in slope.
3. *Sinuosity Change:* Bank loss that occurs during and upon a change in planform or stream meander configuration. This bank loss is usually accompanied by accretion somewhere else along the affected reach.

*Groundwater Erosion:* Groundwater erosion is the removal of soil caused by groundwater seepage or movement toward a free face. Such erosion is commonly referred to as piping. The phenomenon is also known as spring sapping—literally the detachment and movement of soil particles at the point of emergence of a spring or seep in the ground. Piping occurs when seepage forces exceed intergranular stresses or forces of cohesion.

Pipes can form in the downstream side of earth dams (Sherard et al., 1972), gully heads, streambanks, and slopes where water exits from the ground. Once a pipe or cavity forms, it enlarges quickly because flow lines are attracted to areas of lower flow resistance, and this in turn results in further concentration of flow lines or flow net density in a positive feedback cycle.

## 2.5 SOIL LOSS PREDICTIONS

### 2.5.1 Historical Development

A semiempirical equation known as the universal soil loss equation (USLE) was developed by the USDA Agricultural Research Service in the early 1960s. A handbook that served as the main reference for this equation was first introduced in the mid 1960s (Wischmeier and Smith, 1965). A revised and definitive treatment of the USLE was subsequently published in the late 1970s as Agricultural Handbook 537 (Wischmeier and Smith, 1978). This relationship was developed originally for predicting erosion losses from cropland east of the Rocky Mountains. In subsequent years the USLE was modified and adapted to different regions of the United States (USDA Soil Conservation Service, 1972, 1977) and also for use at urban or highway construction sites (Israelson, 1980). These latter uses have stirred some controversy about the limits and applicability of the USLE and have prompted numerous efforts for further revision (Renard et al., 1991).

The USLE takes into account all the factors known to affect rainfall erosion, namely climate, soil, topography, and vegetative cover. It is based on a statistical analysis of erosion measured in the field on scores of test plots under natural and simulated rainfall. The annual soil loss from a site is predicted according to the following relationship:

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{2-1}$$

where: $A$ = computed soil loss (e.g., tons) per acre for a given storm period or time interval;
$R$ = rainfall factor;
$K$ = soil erodibility value;
$L$ = slope length factor;
$S$ = steepness factor;
$C$ = vegetation factor;
$P$ = erosion control practice factor

### 2.5.2 Applications of USLE

Detailed procedures and charts for estimating soil losses and calculating values for the various parameters in the USLE are given in Gray and Leiser (1982) and Goldman et al. (1986). This information is not repeated herein; instead the objective will be to show which parameters have the greatest variability and effect on soil loss and which can be easily modified or changed.

The climatic factor ($R$) and the erodibility factor ($K$) only vary within one order of magnitude. These factors are essentially fixed for a given site and are not subject to change or modification. The cover factor ($C$) and the topographic factor ($LS$), on the other hand, can vary over several orders of magnitude, as shown in Tables 2-4 and 2-5 respectively. Moreover, unlike the other factors, the cover factor ($C$) and the topographic factor ($LS$) can be modified substantially to suit a particular erosion control objective. The topographic factor ($LS$) can be modified most easily by reducing slope length, that is by converting a long, steep slope into a series of short, steep slopes. This is commonly accomplished by benching or terracing. The use of live fascines or contour wattles (see Chapter 7) also achieves the same objective. The placement of fascines at

**TABLE 2-4. Topographic Factors ($LS$) for Slopes**

| Slope Ratio ($H:V$) | Slope Gradient $S$ (%) | $LS$ Values for Selected Slope Lengths $L$ (feet(m)) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 10 (3.0) | 30 (9.1) | 50 (15.2) | 100 (30.5) | 300 (91.0) | 500 (152.0) | 1000 (305.0) |
| 20 : 1 | 5 | 0.17 | 0.29 | 0.38 | 0.53 | 0.93 | 1.20 | 1.69 |
| 10 : 1 | 10 | 0.43 | 0.75 | 0.97 | 1.37 | 2.37 | 3.06 | 4.33 |
| 8 : 1 | 12.5 | 0.61 | 1.05 | 1.36 | 1.92 | 3.33 | 4.30 | 6.08 |
| 6 : 1 | 16.7 | 0.96 | 1.67 | 2.15 | 3.04 | 5.27 | 6.80 | 9.62 |
| 5 : 1 | 20 | 1.29 | 2.23 | 2.88 | 4.08 | 7.06 | 9.12 | 12.90 |
| 4 : 1 | 25 | 1.86 | 3.23 | 4.16 | 5.89 | 10.20 | 13.17 | 18.63 |
| 3 : 1 | 33.5 | 2.98 | 5.17 | 6.67 | 9.43 | 16.33 | 21.09 | 29.82 |
| 2.5 : 1 | 40 | 4.00 | 6.93 | 8.95 | 12.65 | 21.91 | 28.29 | 40.01 |
| 2 : 1 | 50 | 5.64 | 9.76 | 12.60 | 17.82 | 30.87 | 39.85 | 56.36 |
| 1.75 : 1 | 57 | 6.82 | 11.80 | 15.24 | 21.55 | 37.33 | 48.19 | 68.15 |
| 1.50 : 1 | 66.7 | 8.44 | 14.61 | 18.87 | 26.68 | 46.22 | 59.66 | 84.38 |
| 1.25 : 1 | 80 | 10.55 | 18.28 | 23.60 | 33.38 | 57.81 | 74.63 | 105.55 |
| 1 : 1 | 100 | 13.36 | 23.14 | 29.87 | 42.24 | 73.17 | 94.46 | 133.59 |

*Source:* Adapted from Israelson (1980).

**TABLE 2-5. Vegetation Factor *C* Values for Pasture, Rangeland, and Idleland**

| Type and Height of Raised Canopy | Canopy Cover (%) | Canopy Type[a] | *C* Values for Selected Canopy and Ground Cover Conditions (Percent Ground Cover) 0 | 20 | 40 | 60 | 80 | 95–100 |
|---|---|---|---|---|---|---|---|---|
| No appreciable canopy | —— | G | .45 | .20 | .10 | .042 | .013 | .003 |
| | | W | .45 | .24 | .15 | .090 | .043 | .011 |
| Canopy of tall weeds or short brush (0.5-m fall height) | 25 | G | .36 | .17 | .09 | .038 | .012 | .003 |
| | | W | .36 | .20 | .13 | .082 | .041 | .011 |
| | 50 | G | .26 | .13 | .07 | .035 | .012 | .003 |
| | | W | .26 | .16 | .11 | .075 | .039 | .011 |
| | 75 | G | .17 | .10 | .06 | .031 | .011 | .003 |
| | | W | .17 | .12 | .09 | .067 | .038 | .011 |
| Appreciable brush or bushes (2-m fall height) | 25 | G | .40 | .18 | .09 | .040 | .013 | .003 |
| | | W | .40 | .22 | .14 | .085 | .042 | .011 |
| | 50 | G | .34 | .16 | .09 | .038 | .012 | .003 |
| | | W | .34 | .19 | .13 | .081 | .041 | .011 |
| | 75 | G | .28 | .14 | .08 | .036 | .012 | .003 |
| | | W | .28 | .17 | .12 | .077 | .040 | .011 |
| Trees but no appreciable low brush low brush (4-m fall height) | 25 | G | .42 | .19 | .10 | .041 | .013 | .003 |
| | | W | .42 | .23 | .14 | .087 | .042 | .011 |
| | 50 | G | .39 | .18 | .09 | .040 | .013 | .003 |
| | | W | .39 | .21 | .14 | .085 | .042 | .011 |
| | 75 | G | .36 | .17 | .09 | .039 | .012 | .003 |
| | | W | .36 | .20 | .13 | .083 | .014 | .011 |

*Source:* USDA Soil Conservation Service (1978).

[a] G: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 inches deep.
W: Cover at surface is mostly broadleaf, herbaceous plants (as weeds) with little lateral-root network near the surface, and/or undecayed residue.

intervals of 10 feet, for example, in a 100-foot long slope, would reduce the soil loss to one-third of the original value. This reduction can be observed by examining the soil loss or *LS* factor values in Table 2.4 that correspond to a 100-foot long versus a 10-foot long slope for a given slope gradient.

The vegetative cover or *C* factor affects erosion via three separate and distinct, but interrelated, zones of influence, namely canopy cover, ground cover (vegetative cover in direct contact with the soil), and vegetative or crop residue at or beneath the surface. The effects of these three constituent influences can be observed in Table 2-5. For completely bare or fallow ground, the *C* factor is unity. The influence of ground cover is paramount compared to the type, extent, and condition of the canopy. This influence can readily be ascertained by comparing *C* factor values in the row versus column headings of Table 2-5. Even in the absence of appreciable canopy, the *C* factor value can drop to a value of only 0.003 when ground cover reaches 95 percent. This corresponds to almost a thousandfold reduction in erosion losses over the fallow or bare-ground case. None of the other variables or factors are amenable to management with such dramatic results as this one. Mulches and biotechnical ground covers (nets, erosion control blankets, turf reinforcement mats, etc.) provide initial erosion protection and enhance vegetative establishment and performance. They too can be assigned *C* factor values that are useful for evaluation and comparison, as shown in Table 2-6.

**TABLE 2.6 Factors for Different Ground Covers**

| Type of Cover | *C* Factor | Soil Loss Reduction (%) |
|---|---|---|
| None | 1.0 | 0 |
| Native vegetation (dense, undisturbed) | 0.01 | 99 |
| Temporary seedings: | | |
| 90% cover, annual grasses, no mulch | 0.1 | 90 |
| Wood fiber mulch, 0.75 ton/acre, with seed | 0.5 | 50 |
| Excelsior mat, jute netting (slopes up to 2 : 1 | 0.3 | 70 |
| Straw mulch | | |
| 1.5 tons/acre (3.4 t/ha), tacked down | 0.2 | 80 |
| 4.0 tons/acre (9.0 t/ha), tacked down | 0.05 | 95 |

*Source:* Goldman et al. (1986).

Mulches provide immediate protection on bare soils and may perform better than temporary seedings in certain instances. Straw is particularly effective as a mulch and ground cover (Kay, 1983). Straw that has been tacked down provides better protection (lower soil loss) than wood fiber mulch at equal application rates. Mulches and biotechnical ground covers are described and evaluated in greater detail in Chapter 9.

Factor *C* values tend to change with time following certain types of surface treatment such as mulching, seeding, and transplanting. For example, factor *C* values for grass may decrease from 1.0 (for fallow, bare ground) to about 0.01 between time of initial seeding and full establishment. In this case an average or weighted factor *C* value can be computed for a construction period using time as the weighting parameter and estimating *C* factor values for successive time intervals (Gray and Leiser, 1982).

The erosion control practice factor, or *P* factor, has been interpreted in several ways. These practices can be viewed as stuctural-mechanical, hydraulic, or grading practices that reduce the velocity of runoff and/or the tendency of water to flow directly downslope. Structural measures include grade stabilization structures (chutes, flumes, check dams, water ladders), level spreaders, diversions, and interceptor berms. Even sediment basins can be classified and evaluated as a form of control practice. Basins do not stop erosion; instead, they keep eroded material from leaving a site and causing off-side damage. Methods for determining and assigning factor P values for structural measures and basins are given elsewhere (U.S. Environmental Protection Agency, 1973).

In agricultural uses of the USLE, the *P* factor is often employed to describe different plowing and tillage practices. In construction site applications, on the other hand, *P* factor reflects the condition of the ground surface after grading operations. The ground surface condition or roughness can be affected by tractor treads and by raking, disking, or rolling, as shown in Table 2-7.

Some interesting trends can be observed. A slope left in a compacted and smooth condition is the most vulnerable to erosion; it is also the least amenable to vegetative establishment by seeding. Trackwalking up and down slope is

**TABLE 2.7. Ground Surface Condition Factor *P* Values**

| Surface Condition | *P* Factor |
|---|---|
| Compacted and smooth | 1.3 |
| Trackwalked along contour | 1.2 |
| Trackwalked up and down slope | 0.9 |
| Punched straw | 0.9 |
| Rough, irregular cut | 0.9 |
| Loose to 12-inch (30-cm) depth | 0.8 |

*Source:* From Goldman et al. (1986).

superior to trackwalking on contour because the orientation of the tractor cleats is parallel to the slope in the former. Cleat indentations oriented up and down slope can become the locus of rills, as shown in Figure 2-6. As noted in Table 2.7 changing the surface condition does not have a large effect on soil loss since all the factor *P* values are close to unity. On the other hand, the degree of surface roughness and orientation of indentations does have a significant influence on the lodgment of seed and establishment of vegetation on a slope, as shown in Figure 2-7.

**Figure 2-6.** Accelerated rill erosion as a result of trackwalking across the slope, which resulted in cleat indentations oriented up and down slope.

**Figure 2-7.** Lodgment of seed and establishment grass in cleat indentations oriented parallel to the slope.

### 2.5.3 Limitations of USLE

The USLE is an empirically based equation that predicts sheet and rill erosion from relatively small areas. Although it explicity takes into account all the factors known to affect rainfall erosion and is widely employed around the world, it has the following limitations:

- *It is Empirical.* Considerable judgment is required in assigning correct values to some of the factors in certain situations. This is particularly true in the case of the vegetation or cover factor.
- *It Predicts Average Annual Soil Loss.* The rainfall factor is based on the 2-year, 6-hour rainfall. Unusual storms or weather events during a particular year could produce more sediment than predicted.
- *It Does Not Predict Gully Erosion.* The USLE predicts soil loss from sheet and rill erosion, not erosion resulting from concentrated flow in large channels or gullies.
- *It Does Not Predict Sediment Delivery.* The USLE predicts soil loss, not sediment deposition. Soil lost from the upper portions of a slope or watershed will not automatically end up as sediment in a body of water. Instead it may collect on the lower portions of a slope or watershed.

In spite of its limitations, the USLE provides a simple, straightforward

method of estimating soil losses, identifying critical areas, and evaluating the effectiveness of soil loss reduction measures. It provides a rational basis for sizing sediment basins and other sediment collection systems at construction sites. Significantly, the USLE provides an idea of the range of variability of each of the parameters, their relative importance in affecting erosion, and the extent to which each can be changed or managed to limit soil losses.

## 2.6 EROSION CONTROL PRINCIPLES

Surficial erosion can be controlled or prevented by observing some basic principles. These principles are universally applicable; they should be observed regardless of whether conventional or soil bioengineering treatments are contemplated. Erosion control principles are based on common sense, but are frequently violated in site development work. Many erosion control measures and products have been introduced over the years; they are more effective when applied in conjunction with the principles that are enumerated below:

1. Fit the development plan to the site. Avoid extensive grading and earthwork in erosion prone areas.
2. Install hydraulic conveyance facilities to handle increased runoff.
3. Keep runoff velocities low.
4. Divert runoff away from steep slopes and denuded areas by constructing interceptor drains and berms.
5. Save native site vegetation whenever possible.
6. If vegetation must be removed, clear the site in small workable increments. Limit the duration of exposure.
7. Protect cleared areas with mulches and temporary, fast growing herbaceous covers.
8. Construct sediment basins to prevent eroded soil or sediment from leaving the site.
9. Install erosion control measures as early as possible.
10. Inspect and maintain control measures.

Observance of these ten basic principles will greatly minimize erosion losses. Goldman et al. (1986) discuss and elaborate on their importance.

Some additional discussion is warranted here on the impact of grading practices on soil erosion. Both transportation corridors and residential developments in steep terrain require that some excavation and regrading be carried out to accommodate roadways or building sites. The manner in which this grading is planned and executed, and the nature of the resulting topography or landforms that are created affect not only the visual or aesthetic impact of the development but also the mass and surficial stability of the slopes and effectiveness

of landscaping and revegetation efforts. A linear or planar slope will exhibit higher soil loss than a slope with a concave or decreasing gradient near the toe. Likewise, drainage channels brought down and across a slope in a curvilinear manner, which lengthens flow path and reduces gradient, are less susceptible to erosion than exposed channels brought directly down the face of a slope. Landform grading techniques (Schor, 1992, 1993) greatly mitigate erosion problems by observing these concepts and mimicking stable, natural slopes. Landform grading concepts are discussed further in Chapter 4.

## 2.7 NATURE OF MASS MOVEMENTS

### 2.7.1 Types of Slope Movements

Various schemes have been proposed over the years for classifying and describing slope movements (Sharpe, 1938; Varnes, 1958, 1978). Essential characteristics and attributes of mass soil movements are summarized in Table 2-8. The

**TABLE 2-8. Basis for Classifying Mass Soil Movements**

*A. Materials*

1. Ice
2. Rock (jointed, weathered, bedded, folded)
3. Soil (dry or saturated, sandy vs. clayey)

*B. Velocity*

1. Rapid (seconds → minutes): rockfalls, avalanches, earthflows
2. Intermediate (minutes → hours): debris slides, block glides, slumps
3. Slow (days → years): creep, solifluction, lateral spreading

*C. Failure Mechanisms*

1. Slides: Movement along well-defined sliding or shearing surface of largely intact block masses of earth and rock.
   a. *Planar:* Occurs in slopes where there is some geologic control, e.g., bedding planes, joints, colluvium mantle; also shallow slides (sloughing) in homogeneous sandy slopes.
   b. *Rotational:* Occurs in slopes composed of homogeneous, cohesive soils in which resistance to sliding is independent of depth; critical sliding surface tends to be an arc passing deeply under slope where shear resistance is lowest and shear stresses high.
2. Flows: Quasi viscous flow in which it is difficult to detect a distrinct sliding surface; motion dies out with depth; tends to occur in saturated soils (sands, silts, clays) with a high water content.
3. Falls: Falling mass of material loses coherent contact with stable, unmoving base; occurs in jointed brittle rock forming steep slopes.

classification system proposed by Varnes (1958, revised 1978) is perhaps the most useful and widely adopted. His system is based on two main variables:

1. Type of movement
2. Type of material

Types of movements or failure mechanisms are divided into five main groups: falls, topples, slides, spreads, and flows, as noted in Table 2-9. Materials are divided into two classes: rock and engineering soil. Soil is further divided into debris and earth. Debris is material that is transitional in gradation between rock and earth. An abbreviated version of Varnes (1958) classification system is presented in Table 2-9.

A comprehensive description of the various types of slope movements is outside the scope of this book. The interested reader should consult the original papers by Varnes (1958, 1978) for this purpose. On the other hand, it is important to understand and to be able to identify various types of slope movements, not only for purposes of avoiding unstable slopes but also for designing prevention and control systems. Methods useful for prevention and control of one type of slope failure (e.g., shallow, translational sliding) may be ineffectual against deep-seated rotational failures).

### 2.7.2 Causes of Slope Failure

The mass stability of slopes is governed by topographic, geologic, and climatic variables that control shear stress and shear resistance in a slope. Slopes fail when shear stress exceeds shear strength along a critical sliding surface. The factor of safety of a slope is defined as the ratio of shear strength to shear stress along a critical failure surface. The surface with the lowest ratio is the critical or failure surface. This surface also demarcates the boundary between stable and moving ground. The term slide implicitly specifies relative motion between the

**TABLE 2-9. Abbreviated Classification of Slope Movements**

| | | Type of Material | | |
|---|---|---|---|---|
| | | | Engineering Soils | |
| Type of Movement | | Bedrock | Predominantly Coarse | Predominantly Fine |
| Falls | | Rock fall | Debris fall | Earth fall |
| Topples | | Rock topple | Debris topple | Earth topple |
| Slides | | | | |
| Rotational | Few units | Rock slump | Debris slump | Earth slump |
| Translational | Many units | Rock block slide | Debris block slide | Earth block slide |
| | | Rock slide | Debris slide | Earth slide |
| Lateral spreads | | Rock spread | Debris spread | Earth spread |
| Flows | | Rock flow | Debris flow | Earth flow (soil |
| creep) | | | | |

*Source:* Adapted from Varnes (1978).

two. Methods of analyzing and computing the factor of safety of slopes against sliding are reviewed in Section 2.8.

Any variable or factor that increases shear stress or conversely that decreases shear strength will tend to cause slope movement. Causes of slope instability or failure have been grouped into these two categories by Varnes (1958), as illustrated in Table 2-10. Timely identification and recognition of these factors is the key to prevention and control of slope movements. Removal of lateral support by either natural or human agencies is probably the most common of all factors leading to instability. This observation suggests the use of buttress or retaining structures at the foot of slopes as a remedial measure. The addition of water to a slope may contribute simultaneously to an increase in stress and a decrease in strength. Water has been implicated as either the primary or a major controlling factor in 95 percent of all landslides (Chassie and Goughnor, 1976). Accordingly, drainage and diversion measures are without doubt among the most effective means of preventing and/or controlling slope failures. Landslide remedial measures and their effectiveness have been discussed by Zaruba and Mencl (1969), Hutchinson (1978), and Schuster (1992).

Vegetation can ameliorate many of the factors and conditions that cause instability. Woody vegetation growing on a slope can increase soil shear strength via root reinforcement, decrease soil moisture stress via evapotranspiration, and increase overall stability as a result of buttressing and soil arching action. The contribution and significance of slope vegetation to the mass stability of slopes are evaluated in detail in Chapter 3.

### 2.7.3 Indicators of Slope Instability

There are several visual indicators of hillside instability that are very useful for identifying areas of potential slope movement. Identification of unstable slopes

**TABLE 2-10. Causes of Slope Failure**

*Increase in Shear Stress*

1. Surcharging slope (structures and fills at top)
2. Removal of lateral support (cuts and excavations at toe)
3. Rapid changes in water level adjacent to slope ("sudden drawdown")
4. Increase in lateral stress (water filled cracks and fissures)
5. Earthquake loading (increases in horizontal or downslope driving forces)

*Decrease in Shear Strength*

1. Increased pore water pressure, which reduces effective stress (storm water infiltration into slope, uncontrolled discharge of water from drains, earthquake induced pure water pressure)
2. Presence of swelling clays (uptake of water with loss of intrinsic cohesion)
3. Weathering and physicochemical degradation (ion exchange, hydrolysis, solutioning, etc.)
4. Progressive failure by shear strain softening

or slopes with a high landslide potential can be made using certain topographic, vegetative, hydrologic, and geologic indicators, as summarized in Table 2-11. Most of these signs of hillside instability can be spotted by a visual reconnaissance in the field. They are signals for precautions or preventative measures that should be employed during and after slope disturbance in the area.

Peck (1967) stated a postulate that is useful for identifying potentially unstable slopes, namely if there is no evidence of old landslides in an area, then it is fairly unlikely that moderate construction activity will start a new one. On the other hand, if old landslides abound, then it is quite likely that even minor construction operations will activate an old slide or lead to a new one.

**TABLE 2-11. Features Indicating Landslides or Areas with High Landslide Potential**

| Feature | Significance |
|---|---|
| 1. Hummocky, dissected topography | Common feature in old and active progressive slides (slides with many individual components); slide mass is prone to gullying. |
| 2. Abrupt change in slope | May indicate either an old landslide area or a change in the erosion characteristics of underlying material; portion with low slope angle is generally weaker and often has higher water content. |
| 3. Scarps and cracks | Definite indication of an active or recently active landslide. Age of scarp can usually be estimated by the amount of vegetation established upon it; width of cracks may be monitored to estimate relative rates of movement. |
| 4. Grabens or "stair step" topography | Indication of progressive failure; complex or nested series of rotational slides can also cause surface of slope to appear stepped or tiered. |
| 5. Lobate slope forms | Indication of former earthflow or solifluction area. |
| 6. Hillside ponds | Local catchments or depressions formed as result of feature 4 act as infiltration sources that can exacerbate or accelerate slope failure. |
| 7. Hillside seeps | Common in landslide masses and areas with high landslide potential; can usually be identified by associated presence of phreatophyte vegetation, e.g., equisetum, cattails, alder, willows, in vicinity of seep. |
| 8. Incongruent vegetation | Patches or areas of much younger or very different vegetation (e.g., alder thickets) may indicate recent landslides or unstable ground. |
| 9. "Jackstrawed" trees | Leaning or canted trees on a slope are indicators of previous episodes of slope movement or soil creep. |
| 10. Bedding planes or joints | Potential surface of sliding for translational slope movements. |

## 2.8 SLOPE STABILITY PREDICTIONS

### 2.8.1 Approaches to Analysis

Numerous methods are available for predicting the stability of slopes and embankments. The two basic approaches are: (1) limit equilibrium analysis, and (2) deformation analysis. Most methods in use today fall into the former category. Limit equilibrium methods explicitly take into account the major factors that influence the shear stress and shear resistance of a slope (Table 2-10). In addition these methods are simpler to apply than deformation analysis. Limit equilibrium methods do not result in calculation of expected slope deformations; however, there are many instances in which precise deformations are of minor concern, provided the material essentially stays in place.

A detailed treatment of slope stability analysis lies outside the scope of this guidebook. The interested reader is referred to geotechnical texts on this subject (Lambe and Whitman, 1969; Morgenstern and Sangrey, 1978; Huang, 1983). The intent here is mainly to review basic concepts of stability analysis and to describe a few methods that are employed in practice. This review will serve: (1) to explain the combination of conditions that can result in slope failure; (2) to identify the relative importance to stability of different soil, slope, and hydrologic variables; and (3) to establish an analytical or quantitative basis for assessing the influence of vegetation on mass stability.

### 2.8.2 Limit Equilibrium Analysis

Limit equilibrium analysis is used to determine the factor of safety for a given slope; it can also be used to determine the effect on the stability of a slope of varying one or more parameters. A number of methods and procedures based on limit equilibrium principles have been developed for this purpose. Regardless of the specific procedure, the following principles (Morgenstern and Sangrey, 1978) are common to all methods of limit equilibrium analysis:

- *A Failure Surface or Mechanism is Postulated.* In the simplest case, idealized slopes are assumed to fail along planes or circular sliding surfaces, as shown schematically in Figure 2-8. More complex failure surfaces can also be proposed and analyzed when slope conditions are not uniform.
- *The Shearing Resistance Required to Equilibrate the Failure Mass is Calculated by Means of Statics.* The potential failure mass is assumed to be in a state of "limiting equilibrium," and the shear strength of the soil or rock in the failure mass is mobilized everywhere along the slip surface.
- *The Calculated Shearing Resistance Required for Equilibrium is Compared with the Available Shear Strength.* This comparison is made in terms of the factor of safety, which is generally defined as the factor by which the shear strength parameter must be reduced in order to bring the slope into a state of limiting equilibrium along a given slip surface.

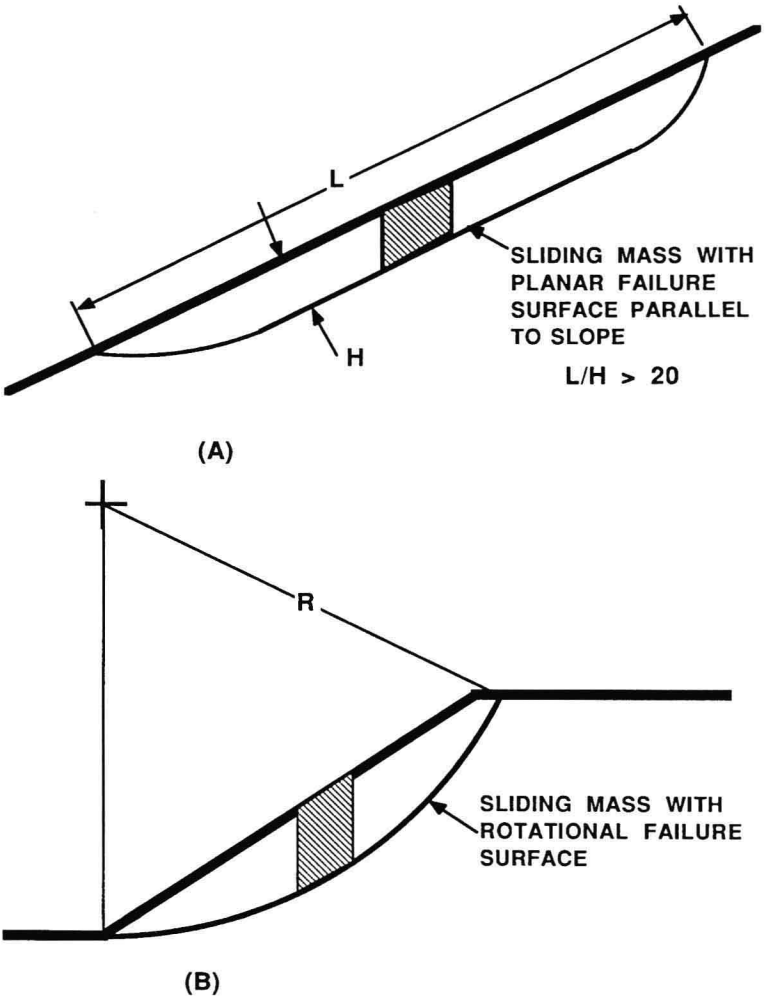


**Figure 2-8.** Slope failure models or mechanisms for mass stability analyses. (*a*) Translational failure, "infinite slope" model. (*b*) Rotational failure, circular arc model.

- *The Mechanism or Slip Surface with the Lowest Factor of Safety is Found by Iteration.* The surface with the lowest computed safety factor is the critical slip surface. If the location of the slip surface is predetermined or constrained by stratigraphic control (e.g., a weak clay seam, relict jointing surface, or contact between residual soil and underlying bedrock), other trials are usually unnecessary.

The essential requirements for conducting a slope stability analysis include the following:

- Accurate description of slope geometry
- Reliable soil properties $(c, \phi, \gamma)$
- Correct definition of external loads, that is, surcharge, line loads, earthquake loads
- Correct description of slope hydrology, that is, phreatic surface (GWT) and seepage conditions
- Correct method of analysis

These constraints and requirements are sometimes difficult to observe in practice. Some common methods of analysis do not rigorously meet all requirements for static equilibrium. This is not as serious a limitation, however, as errors introduced by uncertainty in the proper choice and selection of input parameters, particularly values for shear strength of the soil (Singh, 1970). In spite of these drawbacks and problems, limit equilibrium analysis provides powerful insights into the factors and conditions governing the stability of slopes; it also provides a rational basis for assessing slope hazard and designing remedial measures.

### 2.8.3 Shear Strength Parameters

Determination of the factor of safety by limit equilibrium methods requires an estimate of the shear resistance that can be mobilized along the assumed failure surface. The shear strength of soil or unconsolidated rock is given by the Coulomb failure criterion:

$$s = c + \sigma \tan \phi \tag{2-2}$$

where:
$s$ = shear strength of material;
$\sigma$ = normal stress on the failure surface;
$\phi$ = angle of internal friction;
$c$ = cohesion intercept

The angle of internal friction $(\phi)$ and the cohesion $(c)$ are known as the shear strength parameters. They can be determined from various laboratory tests on representative samples of soil or, alternatively, back-calculated from analysis of a failed portion of a slope by assuming a factor of safety equal to unity.

An important consideration in slope stability analyses is whether to employ a total or an effective stress analysis. This decision determines what type of shear strength parameters must be used in the analysis. General rules and guidelines for selecting the appropriate type of parameters are discussed next and are also presented in Table 2-12 for clay slopes.

***Total Stress Analysis:*** A total stress analysis using undrained shear strength parameters $(c, \phi)$ is limited to slopes where pore pressures are governed by

**TABLE 2-12. Shear Strength Parameters for Clay Slope Stability Problems**

| | Cuttings | | Natural Slopes | |
|---|---|---|---|---|
| Clay Type | Short Term | Long Term | Order of 100 Years | Order of 1000 Years |
| No preexisting slide | | | | |
| Soft, normally consolidated, intact | $\chi \cdot c_u$ | | $c'\phi'$ | |
| Lightly overconsolidated, intact | | $c'\phi'$ | $c'\phi'$ | |
| Stiff, intact | | | $c'\phi'$ | |
| Stiff, fissured | $f \cdot \chi \cdot c_u$ | $r \cdot c', \phi'$ | $c' = 0, \phi'$ | $c' = 0, \phi' \rightarrow \phi_r'$ |
| Jointed clays | $c' = 0, \phi'$ | | | |
| Preexisting slide | $c'\phi_r'$ | $c_r'\phi_r'$ | | $c_r'\phi_r'$ |

*Source:* From Skempton and Hutchinson (1969).

$c_u$ = peak strength, undrained
$c'\phi'$ = peak strength parameters, drained
$c_r'\phi_r'$ = residual strength parameters ($c_r' = 0$)
$\chi$ = reduction factor for rate of testing, anisotropy, etc.
$f$ = reduction factor fissures
$r$ = time dependent reduction factor

total (external) stress changes and in which insufficient time has elapsed for significant dissipation of pore pressures. These conditions are characteristic of the so-called end-of-construction class of problems. A temporary cut made in a cohesive clay slope can be analyzed in this manner, provided it is not fissured and jointed (Table 2-12). A total stress analysis does not require a determination of pore pressure distribution in a slope, an important advantage of the analysis.

***Effective Stress Analysis:*** When pore pressures are governed by steady state seepage conditions, or if long-term stability is a consideration, then stability analysis should be performed in terms of effective shear strength parameters. This is the usual condition for natural slopes in both soil and rock. All permanent cuts or fills also should be analyzed for long-term conditions to see whether these conditions control design (Table 2-12). Some jointed and fissured clays respond to drainage along dominant discontinuities so quickly that they should be analyzed in terms of effective stress regardless of the time of loading or unloading. Effective shear strength parameters ($c', \phi'$) may be obtained from results of either drained triaxial tests or undrained tests with pore pressure measurements (Bowles, 1970). An effective stress analysis requires that effective shear strength parameters be used and that the groundwater table position or pore pressure distribution in the slope be known from piezometric studies. If the pore pressure is unknown or cannot be determined, there is little point to an effective stress analysis; a total stress analysis should be employed instead.

### 2.8.4 Translational Slope Failures

A great number of slope failures can be characterized by shallow, translational sliding. These are also the types of slope failures most likely to be influenced by vegetation and by soil bioengineering treatment. Accordingly, we devote some attention to the analysis of translational failures. The reader is referred to other texts (Huang, 1983) for analysis of deeper seated, rotational failures. The stability of simple, natural slopes where all boundaries (ground surface, phreatic surface, and basal sliding surface) are approximately parallel can be modeled and analyzed by so-called "infinite slope" equations. In this analysis the slip surface is assumed to be a plane roughly parallel to the ground surface.This type of analysis is appropriate when sliding takes place such that the ratio of depth to length of the sliding mass is small, as noted in Figure 2-8. The following types of slopes or slope conditions meet the aforementioned criteria:

1. Loose products of weathering (residual soil) overlying an inclined bedrock contact
2. Inclined planes of stratification dipping downslope and underlain by stronger strata
3. Bedrock slopes mantled with glacial till or colluvium
4. Homogenous slopes of coarse-textured, cohesionless soil (sand dunes, sandy embankments, or fills)

In the first three slopes the surface of sliding is predetermined by stratigraphic control. In the fourth the slope failures are restricted to shallow, surface sloughing because shear strength increases steadily with depth.

Because of the geometry of an infinite slope, overall stability can be determined by analyzing the stability of a single, vertical element in the slope, as shown in Figure 2-9. End effects in the sliding mass can be neglected, and so too can lateral forces on either side of the vertical element, which are assumed to be opposite and equal. The factor of safety based on an infinite slope analysis for the conditions shown in Figure 2-9 is given by the following equation:

$$FS = \frac{[c'/\cos^2 \beta \tan \phi' + (q_0 + \gamma H) + (\gamma_{BUOY} - \gamma) H_w] \tan \phi' / \tan \beta}{[(q_0 + \gamma H) + (\gamma_{SATD} - \gamma) H_w]} \quad (2\text{-}3)$$

where:

$\phi'$ = effective angle of friction;
$c'$ = effective cohesion intercept;
$\beta$ = slope angle of natural ground;
$\gamma$ = moist density of soil;
$\gamma_{BUOY}$ = buoyant density of soil;

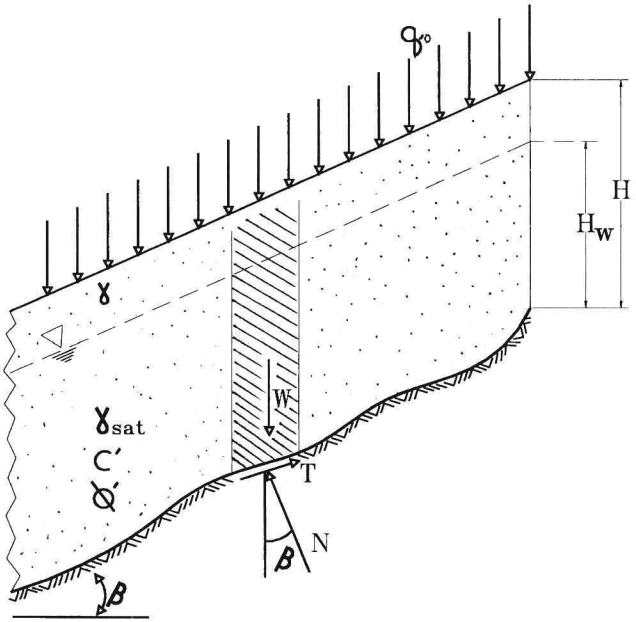


**Figure 2-9.** Schematic representation of idealized "infinite slope."

$\gamma_{SATD}$ = saturated density of soil;
$H$ = vertical thickness (or depth) of sliding surface;
$H_w$ = piezometric height above sliding surface;
$q_0$ = uniform vertical surcharge stress on slope

This expression is quite general and takes into account the influence of surcharge ($q_0$), the presence of a phreatic surface or groundwater table in the slope ($H_w$), and the existence of cohesion ($c'$). The influence of root reinforcement in the soil, which affects only the cohesion and not the soil friction, can be accounted for by adding a "root cohesion" term ($c_R$) to the numerator of Equation 2-3, as explained in Chapter 3. When the groundwater table or phreatic surface is parallel to the slope, as shown schematically in Figure 2-9, seepage also occurs parallel to the surface. An alternative expression can be derived to account for groundwater movement or seepage in other directions, for example, vertically downward or emerging from the slope. These other directions may be important to consider as well, particularly in the case of slope vegetation and soil bioengineering systems that can modify seepage direction near the face of a slope. The influence of seepage direction on the factor of safety is evaluated in Chapter 3.

A number of particular or special cases of interest can be derived from the general expression (Equation 2-3) for an infinite slope. These special cases

include the following:

*Case i) Cohesionless Slope, No Surcharge* ($c' = 0$; $q_0 = 0$)

$$FS = \frac{[\gamma(H - H_w) + \gamma_{BUOY} H_w] \tan \phi' / \tan \beta}{[\gamma(H - H_w) + \gamma_{SATD} H_w]} \tag{2-4}$$

This equation shows the influence of a rise in the phreatic surface in a shallow, cohesionless soil overlying an inclined bedrock contact. Note that the controlling factor is not the absolute rise but rather the ratio ($H_w/H$). In other words, the same rise in phreatic surface is more serious in a "thin" soil mantle than in a "thick" one.

*Case ii) Saturated, Cohesionless Slope, No Surcharge* ($c' = 0$; $q_0 = 0$; $H_w = H$)

$$FS = \{\gamma_{BUOY}/\gamma_{SATD}\} \frac{\tan \phi'}{\tan \beta} \tag{2-5}$$

But for most soils,

$$\gamma_{BUOY} \simeq 0.5 \gamma_{SATD}$$

Therefore,

$$FS = 0.5 \frac{\tan \phi'}{\tan \beta}$$

This equation yields the factor of safety for the worst case of complete saturation of a cohesionless infinite slope. The factor of safety is approximately one-half that of the dry case.

*Case iii) Dry, Cohesionless Slope, No Surcharge* ($c' = 0$; $q_0 = 0$; $H_w = 0$)

$$FS = \frac{\tan \phi'}{\tan \beta} \tag{2-6}$$

This equation shows that in a dry, cohesionless material the critical slope angle is equal to the angle of internal friction of the soil. If the material is end-dumped or side-cast in a loose condition, this angle will be equivalent to the angle of repose.

*Case iv) Stable Slopes with Cohesion, No Surcharge* ($q_0 = 0$; $F > 1$)

(a) *Dry Slope* ($H_w = 0$)

$$c_d/\gamma H = FS \cos^2 \beta \{\tan \beta - \tan \phi'\} \tag{2-7}$$

where: $F$ = desired factor of safety;
$c_d$ = required cohesion

(b) *Saturated Slope* ($H_w = H$)

$$c_d/\gamma H = FS \cos^2 \beta [\tan \beta - (\gamma_{BUOY}/\gamma_{SATD}) \tan \phi'] \quad (2\text{-}8)$$

These equations are useful for determining the amount of cohesion that must be present or developed, for example from root reinforcement, to achieve a desired factor of safety ($FS > 1$) for a given depth of sliding ($H$), slope angle ($\beta$), and friction angle ($\phi'$). Contributions to cohesion from root reinforcement and methods for estimating root cohesion are described in Chapter 3. Note that the required cohesion is directly proportional to the thickness of the sliding mass.

***Selection of Soil Parameters:*** Soil density should be determined in the field using standard procedures for field density testing (Bowles, 1970). Effective shear strength parameters $c'$ and $\phi'$ should be used in an infinite slope analysis when groundwater and seepage conditions are taken explicitly into account. These shear strength parameters can be measured by reconstituting samples in the laboratory to their in-place density and performing a triaxial or direct shear test (Bowles, 1970). Shear strength parameters can also be obtained conveniently in the field by means of an in situ bore hole shear test (Wineland, 1975). An approximate estimate of friction angle can be obtained from gradation and density data using the nomograph shown in Figure 2-10. For many purposes this approximation is satisfactory in lieu of more expensive and time consuming lab strength tests.

***Stability of Road Fills:*** Debris slides that originate from roadway fills are often characterized by movement along an approximately planar surface. One mode of failure is by shallow sloughing of the outside margins of a fill. This failure mode can be analyzed by the conventional infinite slope model, provided the thickness of the sliding mass is small relative to the slope length of the fill. Gonsior and Gardner (1971) suggest a minimum of 20 for the length/depth ratio.

The other mode of failure is sliding of the entire fill along the contact with the underlying natural ground. This mode is common in loose, side-cast fills on steep ground. The roadway in this case is supported part on cut and part on fill, as depicted schematically in Figure 2-11. Many low-volume roads are constructed in this manner. The assumptions of the infinite slope model are not strictly observed in this mode of failure. Instead a "sliding wedge" type of analysis seems more appropriate. Results of such an analysis show, however, that analogous equations describe the factor of safety.

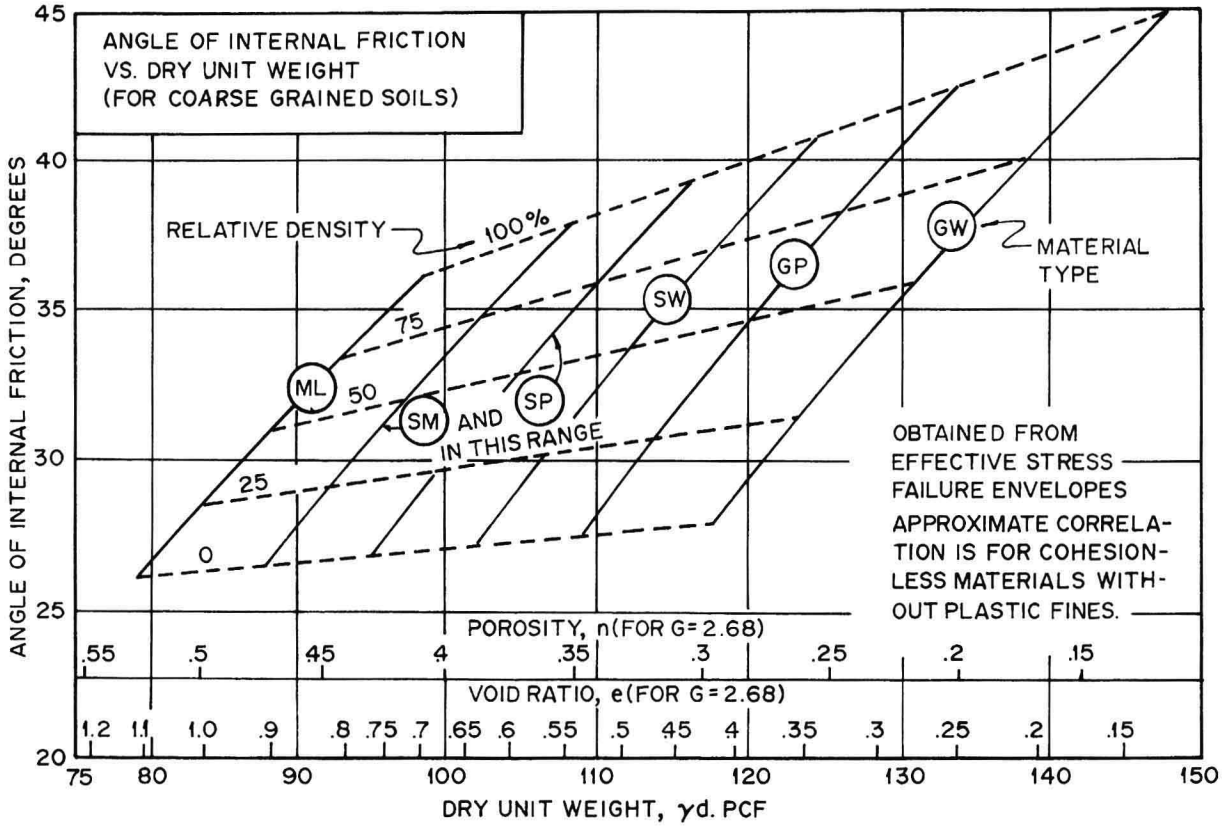


**Figure 2-10** Correlation chart for estimating soil friction angles from graduation and density data. (From U.S. Department of Navy, 1971.)

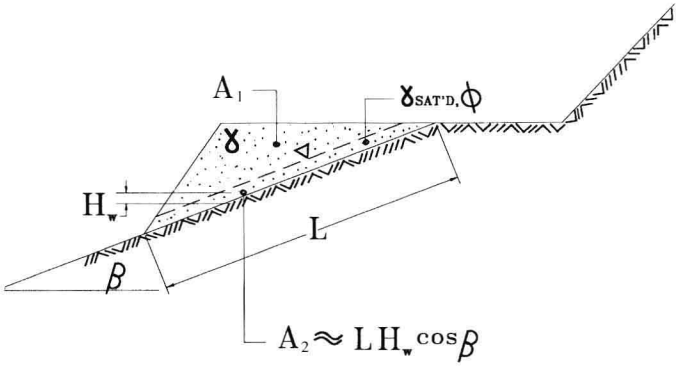


**Figure 2-11.** Schematic representation of roadway supported partly on a bench cut and partly on side-cast road fill. Saturated zone may develop at base of fill along contact with natural ground.

*Case i) Dry Fill, No Cohesion* ($c' = 0$; $H_w = 0$)

$$FS = \frac{\tan \phi'}{\tan \beta} \tag{2-9}$$

In this case both the "sliding wedge" and "infinite slope" model yield the same equation.

*Case ii) Cohesionless Fill with Phreatic Surface near Contact* In this case a thin, saturated zone develops at the base of the fill along the contact with the underlying natural ground, as shown schematically in Figure 2-11. In this case the factor of safety will be given by an equation analogous to the infinite slope equation (Equation 2-4), namely:

$$FS = \frac{[\gamma A_1 + \gamma_{BUOY} A_2] \tan \phi' / \tan \beta}{[\gamma A_1 + \gamma_{SATD} A_2]} \tag{2-10}$$

where: $A_1$ = cross-sectional area of fill above phreatic surface;
$A_2$ = saturated cross-sectional area of fill below phreatic surface

The areas $A_1$ and $A_2$ correspond to the heights $(H - H_w)$ and $H_w$ in Equation 2-4. In some cases fill failures are more complicated and involve material beneath the fill that is activated by the additional fill weight. In those cases the failure surface can cut deeper than the contact with the ground, and the failure surface may be rotational.

## 2.9 CONTROL OF MASS WASTING

Measures to control or prevent mass wasting fall into two basic categories, namely: (1) measures that decrease shear forces, and (2) measures that increase shear resistance. These two approaches are antidotes to the factors that cause mass slope failures (see Table 2-10). Schuster (1992) has presented an excellent and comprehensive review of slope stabilization approaches and techniques.

Water is involved in the great majority of slope failures, because the presence of water both increases shear stresses and decreases shear strength. Accordingly, water drainage and diversion measures are extremely important in mass slope stabilization.

Soil bioengineering measures increase stability mainly by increasing shear resistance either from reinforcement of the soil mantle by roots and/or from interception of shallow slip surfaces by imbedded stems. The contribution to increased shear resistance by woody roots is discussed further in Chapter 3. Some soil bioengineering measures also improve stability by modifying the hydrologic regime in the soil, either by transpiring soil moisture or by acting as drains. Live fascines, elongated bundles of brush buried in shallow trenches, for example, can act as conduits to intercept and facilitate drainage. Live brushlayers inserted between lifts of soil near the face of a slope act as horizontal drains and improve stability by redirecting seepage flow direction in addition to mechanically reinforcing the soil.

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